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Stream channel geometries have been found to enlarge with urbanization of the upland drainage basin. Although enlargement has been documented in a variety of climatic and urban regimes, little is known about how the geomorphic effects of urbanization translate into rural areas downstream. Models derived from Light Detection and Ranging (LiDAR) data from the North Carolina Floodplain Mapping Program were used in conjunction with field surveys to explore the urban-rural transition for North Buffalo Creek in Greensboro, NC. Although the model did not accurately represent at-a-point channel geometries, it was able to represent the prevailing geometric relationships between contributing drainage area and averaged channel capacity for channel reaches of approximately 140m. The urban-rural transition for North Buffalo Creek was found to be linear, with decreases in enlargement beginning well within the current urban boundary. Using linear regression, a truly “rural” state was predicted to be achieved when the channel reaches a contributing drainage area of between 400 - 450km^2. Local increases in enlargement were found to be directly influenced by the junction of major tributaries.

USE OF LIDAR DATA IN DEFINING THE URBAN-RURAL TRANSITION ZONE

IN STREAM CROSS-SECTION MORPHOLOGY

by

Kirsten J. Hunt

A Thesis Submitted to
the Faculty of the Graduate School at
The University of North Carolina at Greensboro
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of the Requirements for the Degree
Master of Arts

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Approved by

____
Committee Chair

To my family, some of the best teachers I have ever known:
my parents, Chuck and Michelle, my sister Rebecca, Laurel and Parker

APPROVAL PAGE

This thesis has been approved by the following committee of the faculty of The Graduate School at the University of North Carolina at Greensboro.

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Date of Final Oral Examination

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CHAPTER I

INTRODUCTION

Stream planform shape and cross-sectional channel geometry (width and depth, as well as the cross-sectional area) are fundamentally a function of geology, climate and drainage basin area. In general, alluvial channels that are not controlled by bedrock tend to increase in both width and depth and in width faster than depth in the downstream direction out of headwaters areas as contributing drainage basin area increases. (Dunne and Leopold. 1978) In areas where a large percentage of the catchment has been disturbed by urbanization, streams have been found to exhibit larger cross-sectional areas than undisturbed channels with similar contributing areas. (Booth, 1991; Chin, 2006; Gregory, 2006; Hammer, 1972). Urban streams tend to exhibit deeply incised channels with steep banks and, given sufficient time, sometimes an inset incipient floodplain. Incised channels in urban environments typically result from channel bed degradation due to the increased stream power associated with increased discharges of storm runoff from impervious surface area in the watershed.

The mechanisms and results of channel enlargement have been well documented, and are indicators of the complex response of streams to changes in catchment land use. Over time, stream channels may adjust to a point where they achieve a new state of meta-stability. It is also possible that perpetual upland disturbance may result in continuous channel change, disequilibrium and unpredictability (Henshaw and Booth, 2000; Schumm, 1977; Wolman, 1967).

Anthropogenic change in channels can also result from more direct causes. Some urban streams have been dredged and straightened (i.e. channelized) by local governments in order to more quickly evacuate storm runoff. Past engineering efforts tended to treat channels like extensions of municipal sewer systems, often with unpredictable and disastrous results (Booth, 1991; Gregory, 2006; Gordon et al., 2004).

In the past twenty years, municipalities have begun to incorporate what is known about channel morphology and evolution into efforts to deal with unstable streams and their negative impacts on ecosystems, property, and landscapes. Channel cross sectional area in particular has become an important measure in the assessment of stream impairment and stability. Stream restorationists commonly use the degree of enlargement of cross sectional area at specific reaches to diagnose the extent to which urbanization has affected stream morphology and stability. Stream restoration efforts then focus on engineering a channel reach so that the channel cross-section more closely resembles that which has been naturally established for an alluvial channel with similar drainage area.

Several studies have included observations of channel morphology before and after entering urban environments, for quantifying urban induced change. Little is known, however, about the nature of channel geometry change as urban streams transition to rural landscapes downstream. Presumably the geomorphic effects of urbanization will disappear at some downstream point, as the growing proportion of the watershed that is in rural land use comes to dominance over urban land use area. The transition could be gradual, as the high volume of urban stormflow decreases with respect to rural contribution, or there could be a pronounced threshold, a downstream distance at which profile dimensions change rapidly. It is also possible that such a distance at which rapid transition takes place increases through time (i.e. moves downstream), and that the spatial change gradient itself increases or decreases through time.

The nature of urban/rural boundaries is particularly important with regard to rural communities downstream of rapidly urbanizing areas. Such information could help to predict areas of downstream instability based on the effects of increased upstream urbanization. With time and observation it may also be possible to monitor the temporal relationship between urbanization and channel change.

Channel cross-section ground survey is a time consuming endeavor which in the end produces a discrete snapshot of form at a given point. There can also be issues with continuous access to stream channels in urban and rural areas with multiple land parcel owners. In order to fully understand the nature of urban-to-rural transitions, there needs to be an inexpensive and efficient method of acquiring continuous data.

LIght Detection And Ranging (LiDAR) is a form of active remote sensing technology from which high-resolution topographic data can be acquired for a large area. It has recently been used to facilitate hydrologic and geomorphologic modeling, and could also be useful in exploring the spatial nature of urban-to-rural channel change (Charlton et al., 2002; Bowen and Waltermire, 2002; Hodgson et al., 2003; Kraus and Pfeifer, 1998; James et al. 2007; Maune, 2001; Ritchie et al., 1994).

In this study, LiDAR-derived digital topographic models are utilized to examine the channel geometry and urban-to-rural cross-sectional change of North Buffalo Creek, a North Carolina Piedmont stream. Digital models are calibrated against channel cross-section measurements made in the field. Channel cross sections are examined with respect to established NC regional curves of channel area, width and depth for urban and rural streams. The goals of the study are to 1) evaluate the potential usefulness and accuracy of LiDAR with respect to mapping headwater channel geometries, and 2) identify the zone of adjustment and the linearity (or nonlinearity) of channel cross sectional adjustment for North Buffalo Creek as it flows from its urban-dominated headwaters in Greensboro, NC downstream into rural eastern Guilford and Alamance counties.

CHAPTER II

BACKGROUND

2.1 – Urban Stream Syndrome and Morphologic Effects

Urban Stream Syndrome refers to a set of hydrologic, geomorphologic and biologic symptoms commonly associated with streams where a significant portion of the contributing upland catchment has been affected by urbanization. Some key features of a stream suffering from the syndrome can include a “flashier” hydrograph with an increased number of peak flows, elevated concentrations of nutrients & contaminants, altered channel morphology (including changes to channel width, depth, cross sectional shape and area, and simplified hydraulic habitat structure), and reduced biotic richness, with increased dominance of tolerant species (Booth, 1991, Walsh et al., 2005).

According to thermodynamic theory, a stream’s equilibrium channel geometry is adjusted to keep total energy expenditure to a minimum (Dunne and Leopold, 1978; Huggett, 2007). As urbanization takes place in a watershed, changes to the contributing upland area including an increase in the area and connectedness of impervious surface area and the concentration of stormflow by physical conduits like sewer systems increase the volume and velocity of stormflow within the channel, leading to increased scour and a higher number of overbank events (Booth, 1991; Dunne and Leopold, 1978; Schueler, 1995).

Additionally, changes to areas immediately adjacent to the channel, including loss of riparian vegetation, can decrease bank and bed stability and lead to increased sediment loads (Booth, 1991). McBride and Booth (2005) found that in Puget Sound watersheds, the urbanization of both the entire watershed and the parts closest to the stream channel had nearly equal weight in influencing the stream's physical condition.

Streams respond to increases in discharge, flow velocity and sediment load by adjusting their channel dimensions through widening, bed degradation (downcutting), and/or overbank deposition of sediment to increase channel depth in areas where degradation is not possible (Booth, 1991; Dunne and Leopold, 1978; Gordon et al., 2004; Gregory, 2006; Walsh et al., 2005). It has been determined that in most settings, urban geomorphologic effects of enlarged channel cross sections are exhibited in streams when the upland catchment reaches and exceeds a threshold of 10% impervious surface area (Schueler, 1995).

The classic United States study of the effects of urbanization on stream cross section was conducted by T.R. Hammer in 1972. Fifty urban watersheds and twenty eight rural watersheds were compared within the piedmont physiographic province in Pennsylvania outside of Philadelphia. Enlarged cross-sectional areas were found in the urban extents. Enlargement was also found to be spatially related to factors such as topography, locations of development within a watershed, and man-made drainage alterations such as sewer systems.

The most critical determinant of the extent of enlargement was the slope of the drainage area, indicating that headwater streams were more prone to urban geomorphic channel enlargement (Hammer, 1972).

From this study, Hammer developed a set of regression models for the urban and rural streams based on Leopold's concept of regional curves, where bankfull discharge was found to be closely correlated with contributing drainage area within climatically and geologically homogenous regions in the United States (Dunne and Leopold, 1978). By comparing the dimensions of urbanized streams to rural streams with equivalent drainage areas, he developed enlargement ratios, measures by which the degree of enlargement from presumed "natural" alluvial dimensions could be assessed for urban streams. Enlargement ratio was also found to be directly proportional to increases in mean annual flood (Hammer, 1972). Since this pioneering study, similar research has been conducted globally. A survey of studies performed in humid to temperate environments worldwide by Chin (2006) found that urbanized streams generally enlarge 2 to 3 times, and can enlarge to as much as 15 times their original size.

2.2 – Equilibrium and the Importance of Local Conditions

Although it is clear that urban areas affect streams, Hammer's findings and the results of other individual studies illustrate the necessity of examining the complex spatial and temporal interactions between historical development, geology and topography, and current land use policies within individual watershed systems. In some environments, urbanization has been linked to a reduction in channel size due to aggradation resulting from increased sediment load (Odemerho, 1992). Kang & Marston (2006) determined that the underlying geology of their study area in the Central Redbed Plains of Oklahoma nullified any geomorphic effects of urbanization on stream channel geometry.

Time is a particularly important factor to consider when studying urban streams, with respect to the inception of urban conditions within the catchment and the stream network's ability to respond to changing conditions. A major concern in attempts at diagnosis and potential remediation is whether or not the system has achieved a state of equilibrium with respect to changes in the surrounding catchment. Although the notion of equilibrium and its identification is dependent on temporal and spatial scales of observation, it is generally thought that in the absence of major changes in external controls (climate and base level) the dimensions of alluvial channels should be characterized by a state of steady-state equilibrium, where channel conditions fluctuate around an overall linear, zero-slope trend (Gordon, 2004; Knighton, 1998; Schumm, 1977). Disturbances such as urbanization can cause fluvial systems to transgress thresholds that make it difficult for the system to adjust back to previous conditions. Given time (absent further disturbance), the channel may achieve a new steady-state equilibrium. However, the amount of time required will depend on the unique properties of the system and the size of the disturbance, and can be especially difficult to predict when there have been multiple disturbances. Wolman (1967) predicted that urbanized channels will remain unstable indefinitely, a theory which remains in debate. Hammer (1972) found that enlargement occurred only in areas that had been urbanized for more than four years and less than thirty years. Ebisemiju (1989) found that the degree and consistency of urbanization create a threshold, where a stable urban stream state was achieved in areas with completely urbanized land uses, but did not predict a reaction time to how long it took before this state was achieved. Henshaw and Booth (2000) concluded that channel geomorphic restabilization of urban streams generally does occur within 1-2 decades of constant watershed land use but it is not universal or well-predicted.

In his 2005 survey of research on the effects of anthropogenic change on natural stream systems, K.J. Gregory identifies the challenges of what he refers to as "feedback effects" in channel management. Disturbances and resulting geomorphologic adjustments at one channel reach can affect an entire system – but not necessarily in a linear (downstream) or temporally predictable fashion. Therefore it is necessary to understand what has happened in other reaches to understand what may happen or is happening at any given location at any given time (Gregory, 2005). Additionally, identifying factors that drive variance in response to urbanization between locations may help in the search for strategies to manage the geomorphologic effects of urban stream syndrome (Walsh et al., 2005).

2.3 – Downstream Urban to Rural Transitions

Although much has been written in documenting the phenomena of urban channel enlargement and stability, relatively little is known about how channel cross sections adjust as streams transition from urban influences into rural areas downstream. Knighton (1998) notes that the effects of urbanization may propagate downstream, and that “the extent to which enlargement is propagated downstream remains unknown”. McBride and Booth (2005) found that that the general symptoms of urban stream syndrome were found to be “improved” downstream if the riparian zone is substantially forested and devoid of road crossings.

One of the few studies specifically mentioning changes in downstream channel hydraulic geometry from urban environments was conducted by Odemerho (1992) in the humid subtropic Ikpoba River basin in Nigeria. Here, urbanization resulted in aggradation due to increased sediment load, with depth reduction accompanying width enlargement. It was observed that reduced channel dimensions did not extend downstream beyond the urbanized reaches, and local change did not alter the downstream log linear trend between channel size and basin area (Odemerho, 1992). The differences in climatic regime, urbanization effects (combination of history & policy) and the small number (2) of downstream survey sites, however, place limitations on the implications of these findings with regards to U.S. streams.

Even fewer studies focus on streams with headwaters falling entirely within an urban area. Most studies document streams that form in rural environments, flow through urban environments, and then transition back into rural environments, thus demonstrating local amplification of peak runoff events within the local urban areas, within a larger flood regime that is predominantly rural.

The limited number of studies on the downstream propagation of the geomorphic effects of urbanization is assumed to be due in part to the focus of remediation on urbanized reaches, and in part to the complexity of individual stream networks and the time required to study an entire system. Geomorphologic measures key to the understanding of fluvial processes, such as bankfull stage, are best assessed through time-intensive measurement and monitoring, while urban stream instability often requires immediate attention. In recognition of this, Gregory (2005) outlines the need for better modeling of stream networks and fluvial processes as a necessity in future study.

2.4 – Introduction to LiDAR and Advantages

Current aerial scanning topographic LiDAR technology was primarily developed in the 1990s. Although refinement of methods and equipment has taken place as the technology has evolved, the basic principles of the earliest systems are the same today. An airborne sensor array emits laser pulses, most commonly in a scanning array perpendicular to the flight path of the aircraft.

Sensors on board the aircraft calculate in-flight global positioning, roll, pitch and heading, and match these factors with the scan angle of the laser pulses and time of return to calculate X-Y and Z coordinates of the reflected point surfaces on the ground. A combination of the scanning angle and flight altitude determine ground point spacing in the in-flight direction, while altitude and velocity determine spacing in the cross-flight direction (Maune 2001).

The use of LiDAR has been shown to greatly improve the accuracy and detail of digital terrain models over those created using earlier techniques such as digitization of topographic quadrangle maps or stereocorrelation/ orthophotographic methods. Expected horizontal and vertical Root Mean Square Errors (RMSE) are frequently less than 1 meter. Point spacing of refined data sets is commonly less than 4m. (Baltsavias, 1999; Hodgson et al., 2003; Kraus and Pfeifer, 1998). Data covering large areas can be collected relatively quickly, and are automatically georeferenced in the collection process. Much of the post-processing and refinement can be quickly accomplished using automated algorithmic processing techniques, eliminating much of the time consuming and costly manual editing associated with other methods. Additionally, many of the temporal considerations associated with traditional orthophotography (cloud cover, time of day, leaf on/off) are much less important to successful LiDAR mapping (Hodgson et al., 2003; Maune, 2001). It has been found that useful topographic results can be achieved in forested areas with a canopy penetration rate of 20-30 percent (Baltsavias, 1999). In the future, it may be possible to extract more detailed land cover classification information in addition to terrain height, by using multiple-return LiDAR and examining return intensities, or by using a variety of laser wavelengths (Baltsavias, 1999).

2.5 – Potential Limitations

There are limitations inherent within LiDAR technology that must be considered when considering a topographic mapping application. The spatial resolution of LiDAR returns renders them ill-suited in defining features with precise boundaries such as the tops and bottoms of stream banks. Accurate definition of such features introduces the need for manual digitization to produce ancillary breakline data from orthophotography or other sources (Maune, 2001). Depending on the resolution of point returns and the look angle of the sensor, the spatial extent of some features may render them too small to be detected at all. For example, the mapping of gullies with a top width of less than 5m was determined to be unreliable using a LiDAR-derived DEM with a 4 square meter resolution (James et al., 2007).

Topography can play a major role in both the horizontal/vertical accuracy and relative spacing of LiDAR returns. The slope of the reflecting terrain can contribute to error in several ways: through shadowing, where a lack of vertical returns in areas with sudden changes in relief result in underestimation of depth and through scatter from steep gradients, which results in a general reduction of point spacing. Additionally, the methods employed by many automatic filtering methods to filter buildings from bare-Earth surfaces tend to also filter or smooth natural features with similar properties, such as stream channels with steep banks (Kraus and Pfeifer, 1998; Bowen and Waltermire, 2002; James et al., 2007; Maune, 2001). Topographic LiDAR returns from water features are also generally unreliable, as points that hit the surface may be absorbed or scattered. The edges of water bodies are also best determined using ancillary breakline data (Maune, 2001).

Point spacing of LiDAR returns are also affected by land cover. In densely vegetated areas, a near-vertical pulse is needed to effectively penetrate canopy and generate a true bare-earth return. In a study of forested areas, Kraus and Pfeifer (1998) found that canopy penetration was often less than 25 percent. Results from a similar study conducted by Hodgson et al. (2003) indicated that in relatively flat forested areas (with slopes of less than 10 percent), land cover has the greatest effect on elevation error, with a general tendency to over predict elevation regardless of land cover category. Additionally, the mean distance to the nearest LiDAR point was closely tied to land cover class, with the greatest point spacing in deciduous, mixed, and scrub/shrub environments (Hodgson et al., 2003).

2.6 – Application of LiDAR to Riparian/Hydrologic Analysis

An early application of LiDAR technology was applied to measuring channel and gulley morphology in locations in Oklahoma and Mississippi. By connecting minimum elevation measurements with straight and curvilinear lines using “best judgment” practices, the authors were able to make rough estimations channel widths and depths (Ritchie, 1994). Bowen and Waltermire (2002) sought to identify the types of river corridor terrain most commonly associated with largest measurement errors in the Western United States. For the stream cross sections measured in their study, large LiDAR elevation overestimations were found to be common in areas with both dense vegetation and steep banks. The authors attributed the greatest percentage of overall error to slope and resulting horizontal (X,Y) positioning limitations. They also determined that vegetation filtering algorithms were less effective along stream channels where dense vegetation was located in narrow bands along low floodplain terraces. Charlton et al. (2002) evaluated the abilities of LiDAR to map gravel bed braided streams in the United Kingdom, and found that error was introduced by both the presence of vegetation and by deep water, which tended to produce gaps in the point spacing.

James et al. (2006) used LiDAR to map the development of gullies and headwater streams under forest canopy in South Carolina. Overall, the model captured the spatial location of gully networks accurately, with errors in the measurement of gully channel dimensions. The 3m point spacing of the data set supported development of 4x4m Digital Elevation Models (DEMs); as such, most of the actively developing gully head cuts (less than 5m in width) were too small to be detected. In larger channels, bank slopes steeper than 60 degrees resulted in shadowing and an underestimation of depth. Overestimation of channel width was tied to point spacing. The authors noted the drawbacks of automated post-processing by which points are removed in areas with sudden changes in slope with respect to this application, and recommended the inclusion of more points in future processing standards to avoid errors of omission. Additionally, the incorporation of ancillary data such as breaklines to explicitly delineate the rims and bottoms of channels was recommended (James et al., 2007).

The above referenced studies illustrate that precise width and depth channel dimensions extracted from LiDAR data sets are likely to be inaccurate. However, if the limitations of the methods with respect to topography and land cover are constant, then scaled relationships between model and nature should be attainable. It is postulated that a channel modeled with LiDAR returns is likely to demonstrate overestimated X,Y dimensions (channel width) and underestimated Z (channel depth). If extracted model geometries are driven by predictable or consistent error, then a downstream pattern of geomorphic response to urbanization should be apparent. Regression of modeled vs. ground survey data might enable the determination of the correct scaling factor and allow comparisons to other ground survey data sets such as those used in the production of regional curves of channel dimensions (Doll et al., 2004). A successful model would permit the analysis of the urban-rural channel transition, including its downstream distance and rate and nature of change in high spatial detail. Such an outcome is the fundamental goal of this research. If errors prove to be unpredictable, then at the very least this exercise should help to identify combinations of factors resulting in accurate and inaccurate reaches of the model, which can then assist in targeting manual fieldwork to those channel reaches with characteristics not suited to modeling.

The exploration of urban and rural sections of North Buffalo/Buffalo Creek might help to identify any potential localized influences that cause the stream to respond in a manner inconsistent with the regional curves. If the system is in a state of quasi-equilibrium, there should be a marked transition from urban to rural channel areas and enlargement ratios as the channel flows downstream of the urban influences of Greensboro. Close examination of a number of cross sections should allow for description of the nature of this transition, and lend possibility of specific factors affecting the change.

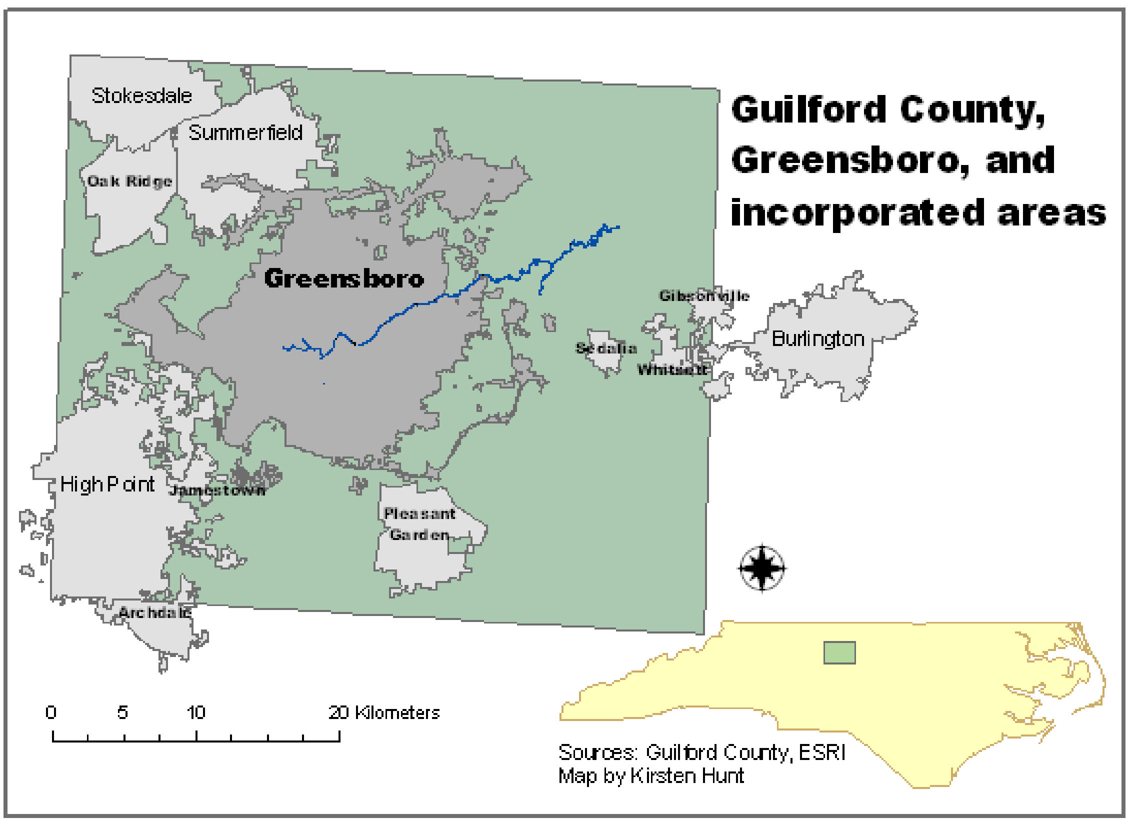
CHAPTER III

STUDY AREA

North Buffalo Creek (NBC) is a North Carolina Piedmont stream that heads in fully urban areas of Greensboro, N.C., population 235,000 (Figure 1). The region falls within the humid subtropical climate zone, with an average annual temperature ranging from 8 to 21 degrees Celsius and an average annual rainfall of 107.4 cm. Native vegetation consists predominantly of mixed deciduous and coniferous trees and shrubs. Soils consist of residuum from mostly granitic rocks and fall largely within the Ultisol order, marked by clay-rich B-horizons. At the scale of interest there are no major geologic changes or transitions that would affect the broader relationships between drainage area, discharge, and channel dimensions.

NBC converges with South Buffalo Creek in rural eastern Guilford County near the city of Gibsonville to form Buffalo Creek, and is a part of the Cape Fear River Basin. The stream has redeveloped bankfull features at some locations following channel incision and cross-sectional enlargement due to urbanization, and currently has no major impoundments. However, Guilford County's growth has been historically fueled by agriculture and milling, and it is probable that some reaches of NBC have been impounded by dams in the past. The channel is partially confined to confined within the surrounding valley, and features some bedrock-constrained reaches. Portions of the channel have experienced past local channelization and/or dredging, the extent of which is not fully known. It is known, however, that NBC at the White Street Landfill has been affected by straightening and dredging within the past twenty years, and potentially by impoundment from dams in the past. NBC at Lake Daniel Park was channelized as recently as 1986. Aerial photography indicates that NBC near Church Street may have been channelized around 1937. It is suspected, though not verified that sites along Buffalo Creek at Huffine Farm Road have also been channelized.

Figure 1. Study Area



Although Greensboro is still growing, the majority of construction activity and transition from agriculture to an urbanized environment within the upland catchment took place in the 1960's. It is assumed that the system has adjusted to urbanization and is in steady-state equilibrium, after 40-50 years of adjustment. Although NBC begins in Greensboro, it is not included in the city's water supply watershed, and is not subject to watershed critical area protections, which dictate development in riparian areas and establish riparian buffers.

Regional curves of stream bankfull cross sectional area, width and depth for the Piedmont of North Carolina were established by The NC State Stream Restoration Institute (Doll et al., 2003). Using data from urban streams in the Piedmont cities of Charlotte, Raleigh, and Winston-Salem and from rural streams in the western part of the Piedmont, this study confirmed that NC Piedmont urban streams do exhibit an increase in channel cross sectional area with respect to rural streams with corresponding drainage areas. The authors also calculated enlargement ratios for each urban reach. Although the Piedmont of NC differs geologically between urban areas, the researchers did not explore potential differences. And although the urban streams studied all head within urban areas, they did not examine how those streams change as they transition into a rural environment.

CHAPTER IV

METHODS

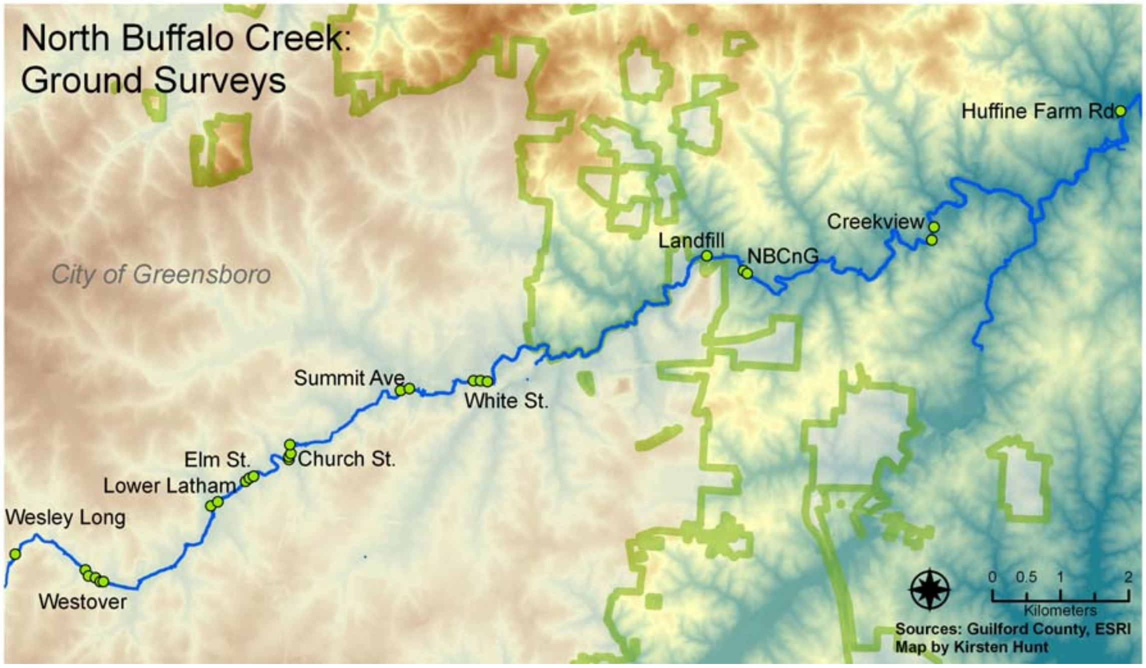
4.1 - Field Surveys

Ground survey measurements of channel cross-sectional dimensions and shapes were collected from multiple sites along North Buffalo Creek with drainage areas between 12 and 230 km^2, and a minimum channel width of 8 meters (Figures 2 and 3, Table 2). Sites were chosen to avoid the spatially immediate effects of natural features such as stream network junctions, and man-made features such as bridges and culverts. Ground surveys provided data on the three critical morphometric variables: cross-sectional area, channel width, and mean maximum channel depth. When present, the location of prominent morphologic features such as benches, point bars and terraces were also noted. Additional information, including presence of bedrock, natural debris dams, bank vegetation types (deciduous vs evergreen, broadleaf vs needle leaf) and average canopy height, were also recorded. These vegetation types were grouped into basic categories (Table 1)

Table 1. Land Cover Type Categories

Land Cover Type	Definition
Open	Few trees/shrubs; banks clearly visible in orthophotography
Mixed 1	Shrub/scrub and/or small trees along one bank, not extending beyond riparian zone
Mixed 2	Shrub/scrub and/or small trees along both banks, not extending beyond riparian zone
Forest	Mixed evergreen and deciduous trees extending beyond riparian area

Figure 2. Ground Survey Locations



Survey work was conducted at the Wesley Long, Elm St., Landfill, and Huffine Farm locations during the summer of 2008. Additional cross-sectional data from the other sites along North Buffalo Creek were obtained from previous research by various members of the North Buffalo Creek Research Group at the University of North Carolina – Greensboro Department of Geography (Royall, 2008).

Bankfull elevation heights were identified at each site using various criteria including the top of well-developed point bars (when present), elevation of broad flat alluvial surface (behind any natural levee) adjacent to the channel (i.e. floodplain) and clear signs of recent coarse deposition (Harman, 2000; USDA Forest Service, 1995). If such flat surfaces were of unequal heights for left and right banks, the lower of the two was taken as the best indicator, assuming levee deposition could be responsible for the more elevated bank. Because of the difficulty of identifying bankfull stage in potentially evolving disturbed channels (like in urban environments) this measure may not always reflect hydrologic bankfull stage (i.e., that flow having recurrence interval of approximately 1.5 years on the annual maximum series for the humid eastern United States) or bankfull channel capacities at each location. Thus, the measure of cross-sectional area will be henceforth referred to as channel capacity.

Channel capacity was calculated at each site using the formula:

Channel Capacity

$\sum (X_{i+1} - X_i)[(Y_i + Y_{i+1})/2]$

where

X_i = cross section distances (widths) to successive vertical depths measured from the left bank

Y_i = vertical depth

Table 2. Field Survey Site Data

Section Name	Drainage Area (SqKm)	Width (M)	Depth (M)	Land Use Cover	Prominent Features	Survey Date
Wesley Long	12.6	12.5	1.19	Mixed 2	to top of left bank (pronounced berm)	2008
Westover 1	24.6	11	2.15	Mixed 1	to top of bank	2005
Westover 2	24.6	12	2.5	Mixed 1	to top of bank	2005
Westover 3	24.6	12.5	2.54	Mixed 1	to top of bank	2005
Westover 4	24.6	9.5	2.73	Mixed 1	to top of bank	2005
Westover 5	24.6	13.5	2.31	Mixed 1	to top of bank	2005
Lower Latham 1	31	16.5	1.49	Open	to top of lower bank	2005
Lower Latham 2	31	17.4	1.88	Open	to top of lower bank	2005
Elm St. 1	35.7	19.5	1.27	Open	to top of lower bank	2008
Elm St. 2	35.7	15	1.4	Open	to top of lower bank	2008
Elm St. 3	35.7	14.5	1.16	Open	to top of lower bank	2008
Church St. 1	36.8	8.5	2.06	Open	to top of rt. bank	2005
Church St. 2	36.8	10.5	2.53	Open	to top of rt. bank	2005
Church St. 3	36.8	9.4	2.49	Open	to top of rt. bank	2005
Church St. 4	36.8	8.5	2.03	Open	to top of point bar	2005
Summit Upstream	57.1	12	2.2	Mixed 2	to top of left bank	2008
Summit Downstream	57.1	12	2	Mixed 2	to bench 0.8 m below top of left bank flat	2008
White St. 1	58.4	11.3	2.85	Forest	to top of high depositional bench; ~0.6 m below highest valley flat	2008
White St. 2	58.4	12	2.07	Forest	to top of high depositional bench; ~0.6 m below highest valley flat	2008
White St. 3	58.4	8.5	2.3	Forest	to top of high depositional bench; ~0.6 m below highest valley flat	2008
Landfill	88.4	16.5	1.65	Mixed 2	to top of lowest bank; left bank well developed floodplain	2008
NBCnG 1	96	14.3	2.44	Forest	to top of lowest bank; left bank with obvious recent overbank sed	2008
NBCnG 2	96	16	2.16	Forest	to top of lowest bank; left bank with obvious recent overbank sed	2008
Creekview Upstream	107.2	14.7	2.5	Forest	to top of high depositional bench; ~0.6 m below highest valley flat	2008
Creekview Downstream	107.2	13.9	2.4	Forest	to top of high depositional bench; ~0.6 m below highest valley flat	2008
Huffine Farm 1*				Mixed 2	excluded; presumed heavily modified	2008
Huffine Farm 2*	233	22	3.7	Mixed 2	to top of lower bank; bankfull level nearer well developed point bar	2008

Figure 3. Photos of Survey Locations

Wesley Long

Westover

Lower Latham

Elm St.

Church St.

Summit (Downstream)

Figure 3. Continued


White Street


Landfill

NBC near Greensboro


Creekview (Upstream)


Buffalo Creek at Huffine Farm

4.2 – Channel Model Data Preparation and Software

LiDAR data for North Buffalo Creek in Guilford County were obtained from the North Carolina Floodplain Mapping Project web site at http://www.ncfloodmaps.com. The data were flown during leaf-off conditions in 2001 as a part of Phase I of the State's comprehensive floodplain mapping program, and meet the State's quality standards with a specified root mean square error (RMSE) of less than 25cm (17.9cm) using 95% of 114 checkpoints in 5 land cover classes.

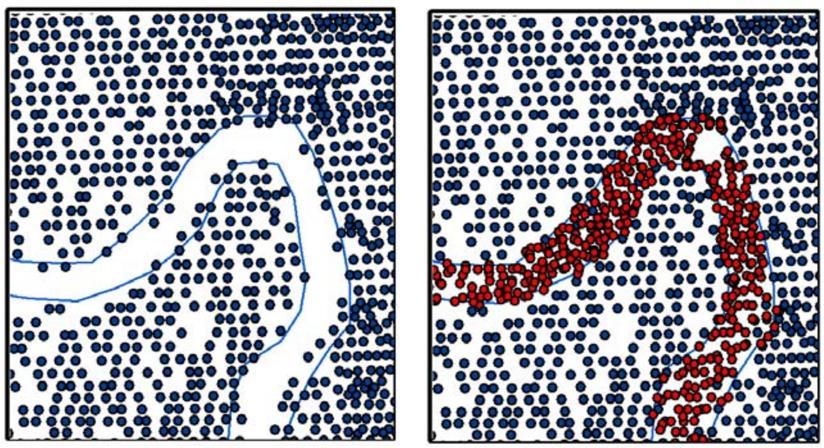
Two data sets, one "bare Earth" point set with a spatial resolution of roughly 3m and its associated breaklines, and a 20m hydrologically correct raster set, were initially obtained for Guilford County. To reduce file size, the 3m set was cropped to an area within 500 feet adjacent to the stream channels, and was used for primary channel modeling. The 20m resolution set was collected for a larger area, encompassing the entire drainage area for each channel, and was used to calculate hydrologic relationships and upstream drainage areas for channel cross sections.

Using ArcGIS, the bare Earth 3m sets were converted to point shapefiles and projected into NAD83 NC State Plane (feet) coordinates, the native projection. Units were then converted to meters for subsequent calculations. The vector point files were then merged and converted to a triangulated irregular network (TIN) file using the Z elevation value (meters) for each point to create a digital model approximating the land's surface.

Breaklines produced by the State and provided with the 3m data set were insufficient for determining channel top-of-bank features for several reasons. When aligned with aerial photography, the State's breaklines most closely correspond with water's edge at the bottom of bank, representing the width of the channel bed rather than width of banks; also, nearly half of the stream length in this study was represented by a single line representing the channel center line, rather than three lines representing the two banks and center line. In order to improve and refine the TIN's depiction of surface elevation changes near the channel, top of bank breaklines were manually digitized using 2002 orthophotography, and verified using contours generated from the 3m TIN as well as the surveyed reaches. These breaklines were converted to 3D lines, and a new TIN was generated.

Each of the State's LiDAR data sets have been subjected to proprietary algorithmic filtering by the acquiring party, with the intent of eliminating non-bare-Earth returns such as vegetation and buildings automatically and without costly manual editing. Although the exact methods are unknown, common techniques include setting height thresholds, and establishing maximum percentages of change in height between adjacent points. This can lead to omission errors, where valid surface returns are eliminated from areas with sudden changes in slope, such as incised urban stream channels. In the 3m bare-Earth data set, automated filtering techniques have resulted in a significant reduction of point density in many areas along the stream channels, particularly between the high banks/levees. As a simple calculation of total area and number of points, the average point density for the bare-Earth data set is 3m. The actual spacing of points, however, is not even. In some areas, the average point density is greater than 3m; in other areas along the channel, there is noticeably greater point spacing (Figure 4, left).

Figure 4. Point Spacing Before and After Addition of Raw Points



In order to consider these potential omissions, “raw” unfiltered LiDAR point return sets were obtained from the USGS Center for LiDAR Information Coordination and Knowledge (CLICK) web site at http://lidar.cr.usgs.gov/. The LiDAR data for Guilford County was acquired in Phase I of the State’s floodplain mapping program, before regulations regarding metadata had been firmly established; thus, the raw set does not contain information identifying multiple returns or return intensity. Point density for these sets are generally three times greater than the processed 3m sets. The supplemental use of raw points in conjunction with the 3m bare-Earth set can increase density within the channel (Figure 4, right).

The raw data was first cropped to areas within 1 meter of the stream bank breaklines. Raw points were then filtered to only include those within 2m of the TIN surface derived from the 3m point set. These points were then merged with the 3m data set to create an enhanced "mixed model" point data set. A new TIN surface was derived from this merged set and the breaklines, and manual editing was performed to eliminate obvious non-Earth (i.e. – lone returns more than one meter higher than surrounding returns) within the channel area.

4.3 - Model Evaluation and Calibration

Channel cross sections were extracted for the locations corresponding to the surveyed sites from the 3m bare Earth and merged raw-bare Earth LiDAR-derived TIN using the 3D line and graph tools in the 3D Analyst extension of ArcGIS. If the TIN model contained nearby in-channel points, 3D lines were constructed at the precise ground survey points along the channel. In some areas, it was necessary to sample the model at a distance as much as three times the channel width either up or downstream from the ground survey location due to insufficient numbers of points in the channel at survey sites to adequately represent depth or due to lack of points representing one or both banks. This decision was based on the geomorphic observation from a large number of studies that repetition of major bed structures like riffles and pools which are often tied to channel geometry characteristics tend to occur on average for most stream types every six channel widths (Knighton, 1998).

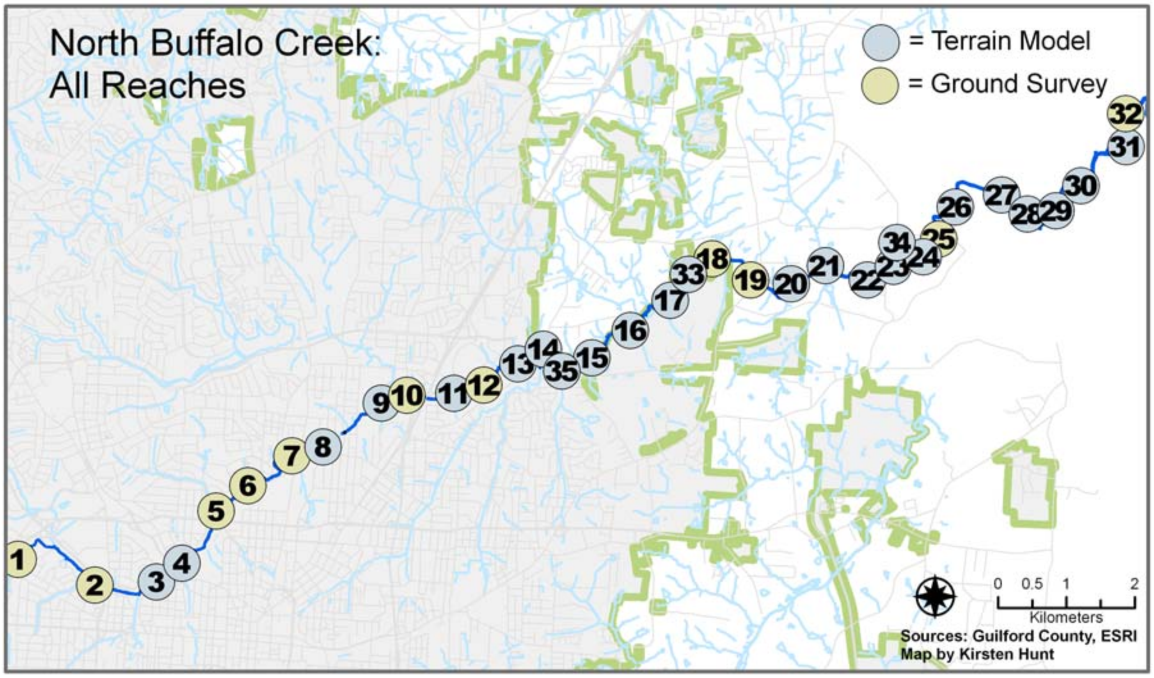
In order to qualify as a potentially representative sample, 3D profiles were chosen based on specific criteria. They needed to capture the lowest top-of-bank, or some other prominent geomorphic feature such as a large bench or top of point bar that was either present in multiple samples, or the equivalent of nearby lowest bank height. In keeping with literature that suggests that LiDAR will overestimate width and underestimate depth at a local scale, qualifying reaches were assessed in the following manner: modeled channel width needed to be at least as wide as the ground survey reach, and could not exceed twice the maximum ground surveyed width (27m), while channel depth needed to be at least ½ the range of all surveyed depths (1.25m).

From these 3D lines, channel width and lowest bank depth were calculated, using the lowest bank to index bankfull height. Channel capacity was calculated using several methods: by calculating the exact area of the extracted cross section, regardless of point spacing and accuracy of channel shape; by calculating rectangular area (W x D), and by a trapezoidal method: $A = h[(b_1 + b_2)/2]$, where the channel bed was assumed to be 2m narrower than the lowest bank width. Modeled channel width, depth, and multiple estimates of channel capacity were then correlated with the same measures from ground survey data to evaluate model accuracy and determine best practice techniques for future extraction. Linear regression of model and ground survey data was used to determine the scaling coefficient, or difference in regression line slope. The correlation and regression process described above was also performed on data representing the averaged reach values for each channel section of like drainage area.

4.4 - Data Extraction from Model

Using best practices from the survey-model correlation, channel cross-sections were then sampled from model reaches stratified at 1 km down valley intervals supplemental to the reaches surveyed in the field (Figure 5). Half meter contours derived from the TIN surface were utilized to select areas that best represented the channel, through a combination of point spacing and range of width/depth values. At least three cross section samples were acquired from each 1 km contiguous reach, constrained to a channel length range of 144 meters (equivalent to the average of the ranges of the ground surveyed reaches) using the same qualifying guidelines outlined in section 4.3. For each cross-section sample, channel width, lowest bank depth, channel capacity, and drainage areas were calculated.

Figure 5. All Survey Points



Increases in the cross-sectional dimensions of channels that are the result of disturbance are conveniently indexed by channel enlargement ratio which compares disturbed channel dimensions to those from relatively undisturbed sites with the same amount of contributing drainage area. Enlargement ratios were calculated for all sites in the following manner:

Enlargement Ratio

xu/xr

where

xu = channel capacity dimension of surveyed or model cross section at a specific drainage area
xr = channel capacity dimension of undisturbed rural channels at the equivalent drainage area as derived from NC Piedmont regional curves (Doll et al. 2004).

CHAPTER V

RESULTS AND ANALYSIS

Correlation (R^2) values for channel width and depth are very low at 0.05 and 0.03 respectively. Examination of scatterplots (Figure 6) reveals that the distribution of points for each measure appears to be in a “megaphone” pattern, with channel terrain modeled width scatter inversely proportional to ground survey width magnitude and channel terrain modeled depth scatter proportional to ground survey depth magnitude. The scatter pattern for width may be explained by the fact that the potential error in channel width caused by suboptimal point spacing of the data represents a greater percentage of the total width measurement in narrower areas of the channel. For the scatter pattern in depth measurements, it is possible that the increase in downstream riparian vegetation and range of water depths downstream may result in a larger percentage of non-bare-Earth returns and thus the observed variation. R^2 for calculated “true” cross sectional area is higher than the generalized rectangular and trapezoidal areas (each at 0.23), but is still relatively low at 0.36.

In nature, stream cross-sectional area is a function of drainage area and discharge. Local variations in one dimension such as width will be balanced by opposing variations in depth because the channel must carry the water supplied by the upland catchment. Within each reach (as defined by common drainage area), it is observed that the differences between the channel capacities of the ground survey points vary much less than the differences between corresponding channel terrain modeled cross sections. This indicates that scatter in the regression model is more likely to be due to error in the channel terrain model, caused by a variety of factors including sub-optimal point spacing and/or returns that do not accurately reflect true width and depth. Because this study is primarily concerned with channel capacity as a function of drainage area, averaging by reach provides a means of finding representative values of channel capacity measures for each site, rather than each transect point. Correlation of these averaged values is thus based on the physical relationship between drainage area and cross-sectional area, rather than on the relationship between specific X-Y points.

Using this logic, the geometric measures for the surveyed reaches were averaged by reach and then correlated with the averaged cross-sectional dimensions from the corresponding terrain modeled reaches (Figure 7). Again, channel terrain model width and depth measures exhibited very weak to non-correlation, with R^2 values of 0.08 and 0.04 respectively; however, R^2 for true cross sectional area improved to 0.73, indicating that although the channel terrain model does not accurately represent local point-specific geometric features, it does represent predominant channel capacity over a reach of several hundred meters. The resulting negatively-sloped regression line and equation indicate that the channel terrain model underrepresents the cross-sectional area of the ground survey points. In order to adjust the terrain model values to values comparable in magnitude to corresponding ground surveyed values, subsequent channel capacity areas extracted from the model were scaled using the formula derived from the surveyed reach regression model:

Survey XU_y = 1.0747(terrain model XU) + 7.0454

where

XU = Channel Capacity.

These values were then averaged by reach.

Figure 6. All Survey Points: Width, Depth and Cross-Sectional Area

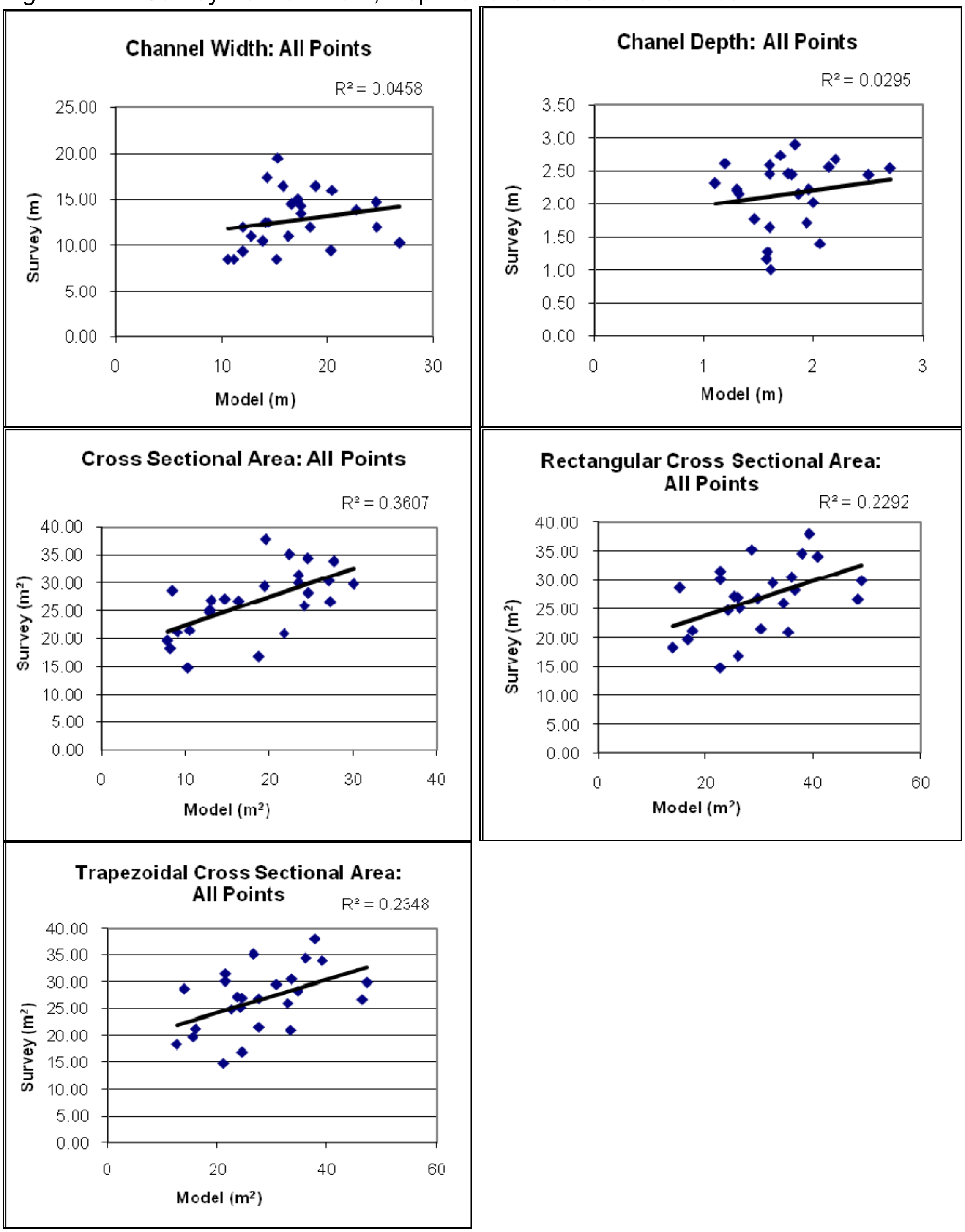


Figure 7. Reach Average Width, Depth and Cross-Sectional Area

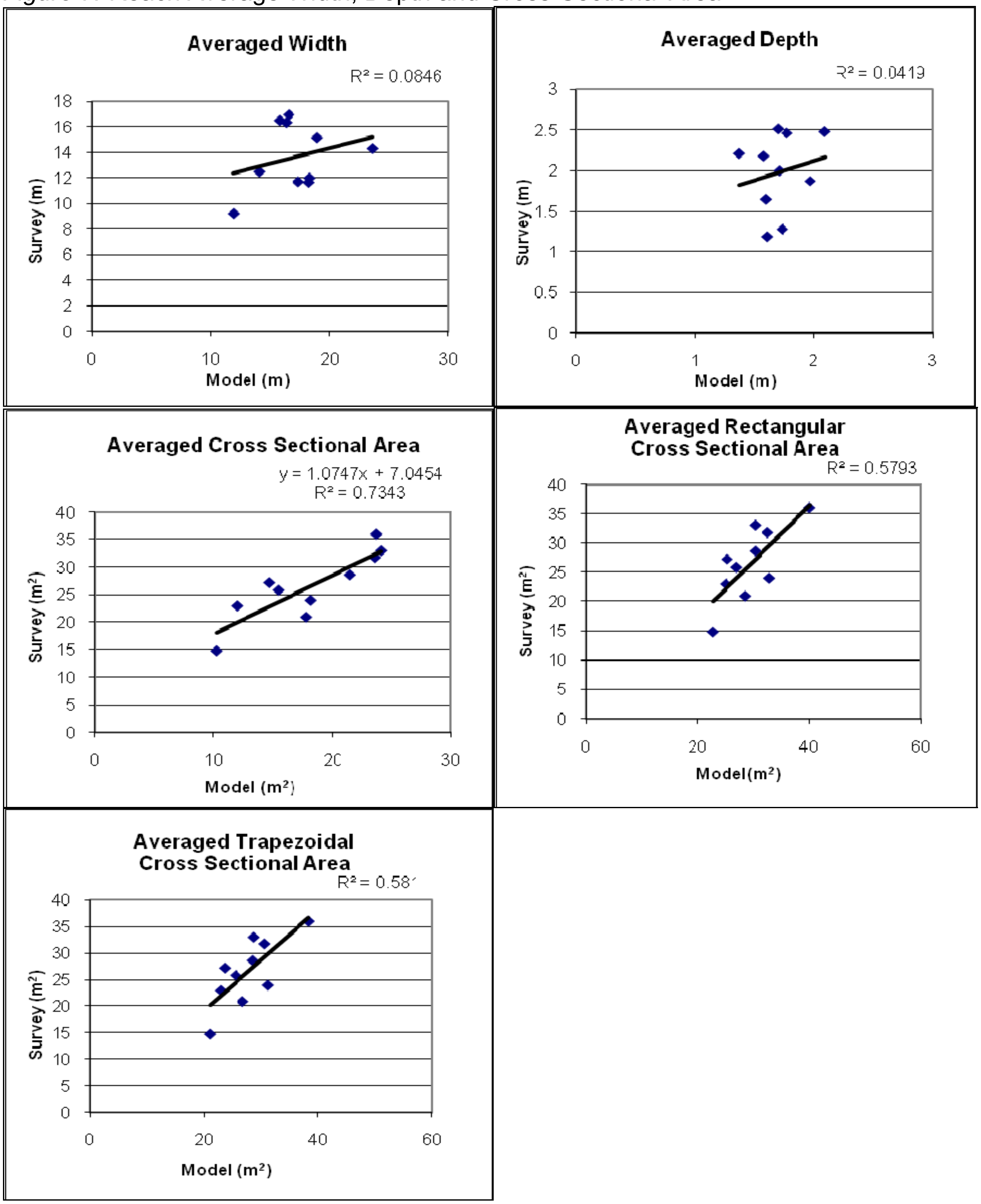
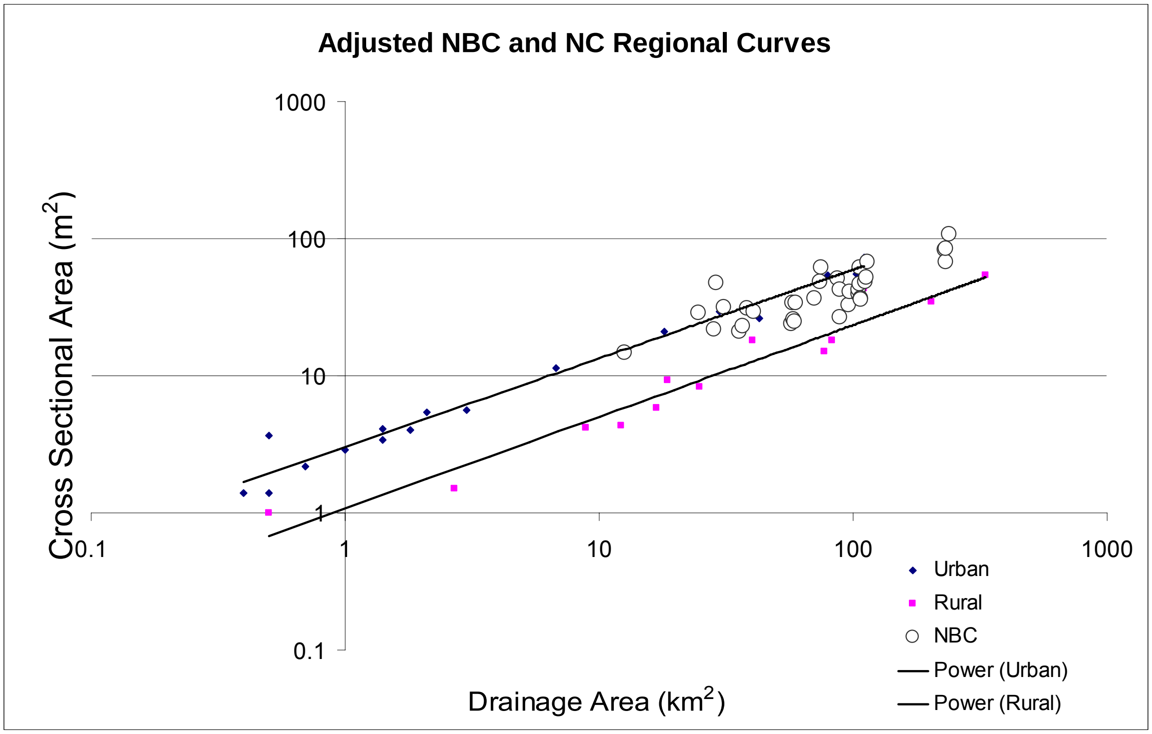


Figure 8 shows the final channel capacity areas (a combination of the ground survey reaches and modeled reaches adjusted using the regression equation described above) plotted against urban and rural regional curves for North Carolina (Doll et al., 2002). In general, NBC channel capacity demonstrates variability between urban and rural proportions within the study area. The decrease in enlargement toward rural reaches begins at drainage areas that are well within the city limits, somewhere between Church St. and Summit Avenue. Channel capacity does not reach the rural curve within the study area. Although the points do not contact the rural regression curve, some of them seem clearly to fall within the scatter envelope for the rural regression. This means that they are at least comparable to some of the rural sites.

Figure 8. North Buffalo Creek and NC Regional Curves



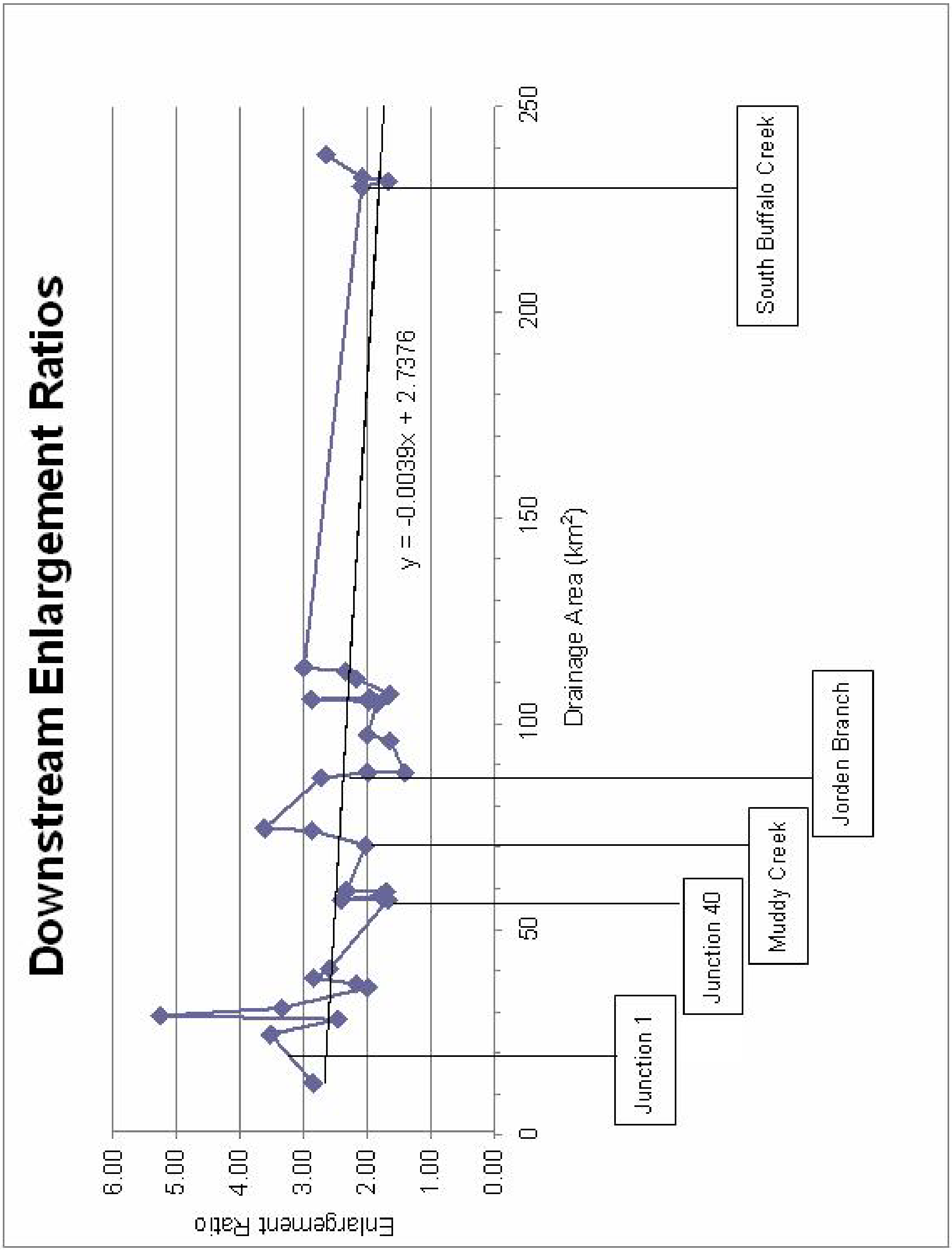
Channel enlargement ratios were plotted against drainage area to illustrate downstream trends (Figure 9). Although changes in enlargement ratio produced by tributary confluences are apparent in the data, overall enlargement ratios appear to generally decrease in a linear fashion with increasing drainage area. This decrease begins well within the city limits near the Elm Street/Church Street reaches. Regression lines were fitted to the enlargement ratio values as well as values produced by moving average filtering (window = 3). Using the slope of these lines, it is estimated that enlargement ratios will reach 1 (true rural proportions by the NC regional curves) when the stream reaches a contributing drainage area of between 412 and 446 km^2.

The downstream location of stream junctions & potential channel obstructions (bridges, etc.) were mapped by downstream distance and drainage area, and tributaries introducing significant relative proportions of drainage area are indicated on the downstream enlargement ratio graph (Figure 9). Increases in enlargement ratio appear to strongly relate to major tributary junctions. Additional reaches were sampled from the model to confirm trends and provide greater resolution in areas of flux (Figure 5, non-sequential point numbers). It is observed that downstream increases in enlargement due to tributary junctions do not persist more than 1km downstream from the junction, and rarely persist beyond ½ km. In the case of the junction with South Buffalo Creek, it is possible that the enlargement extends upstream from the confluence. The survey point taken 100m upstream from the confluence at 113.5m in drainage area (Point 28, Figure

5) has an enlargement ratio of nearly 3, while Point 29 (Figure 5), taken just downstream from the confluence has an enlargement ratio of 2 (also see Figure 9). Upstream enlargement may be caused by the upstream migration of bed degradation resulting from the increase in discharge and channel scour at the confluence, or a combination of degradation, bank failure due to frequent flooding and saturation of the banks at the junction, and possible increased local flooding as a result of a constriction (a road bridge) just downstream from the confluence. Alternatively, sediment aggradation at the confluence could have resulted in increasing bank heights. In this scenario bed and bank aggradation is caused by the pooling of water and sediment at the confluence. This increases bank height, but the increase in bed sediment is quickly removed by smaller subsequent floods that do not top the banks. Thus, increase in both depth and width result. Furthermore, this local aggradation at the confluence might explain why the enlargement ratio abruptly declines immediately downstream (which would receive sediment from this area as well) before enlarging once again. This is indicative of the stream's geomorphic ability to respond to sudden major changes in drainage area and discharge at a local scale.

The exception to this observation, the cross sectional samples representing the point exhibiting the largest residuals (Point 4, Figure 5), were taken from an open industrialized area bordered by highway interchanges. It is presumed that the channel here may have been heavily modified, and that this is not indicative of a large-scale response to the upstream Junction 1.

Figure 9. Downstream Enlargement Ratios and Tributary Junctions



CHAPTER VI

DISCUSSION

6.1 – Data and Potential Sources of Error

It is important to note the distinction between data from the NC regional curves, where area was calculated as a function of bankfull stage, and this study's measure of channel capacity. Bankfull stage is believed on both theoretical and empirical grounds to represent the dominant discharge at which the most geomorphic work is accomplished with respect to channel shape, and is a key measure in assessing the state of a fluvial system. Because it can differ from place to place, estimation of bankfull stage at a given channel reach inherently requires local field study and monitoring of historic records of discharge. However, in North Buffalo Creek, it is thought that channel capacity based on lowest bank height is an acceptable index of bankfull cross-sectional area. Records from hydrologic monitoring stations along North Buffalo Creek indicate that the recurrence interval for lower bank flood events at several survey sites including Westover and Church St. is between 1.5 and 1.6 years, which is equivalent to the expected recurrence interval for bankfull events in most eastern United States streams. Field observations of channel features and sediment deposition and movement also support this hypothesis (Royall, 2008).

In urban environments, a variety of factors influence channel geometry other than drainage area. These factors include percentage of impervious surface area, underlying geology, topography (including channel slope), and historical change within the catchment and to the channel. Although the primary focus of this study was the effect of drainage area, the interaction of all of these factors should be more carefully examined within the NBC basin, and in any future study within other basins.

Low point density in the area along the channel is thought to be the dominant source of error between the surveys and the model, most likely the result of a combination of factors detailed in Chapter II. Table 3 details the averaged absolute values of residuals for the survey location modeled width, depth and cross sectional area by vegetation category. In general, it appears that measures from less-vegetated reaches carry less error, and that measures of width are more consistently affected by vegetation. It is postulated that if the residuals are a result of natural channel change, they would increase in magnitude downstream; if they are a result of consistent terrain model error, they will remain the same in absolute magnitude. Although relative point spacing within the modeled channel tends to decrease as the channel increases in width downstream, the points that do fall within the channel appear to convey more accurate estimations of depth and cross-sectional profile graphs better represent channel shape than those taken from upstream.

Table 3. Residuals for Survey Sites by Land Cover Type

Measure	Vegetation Category				
	Open	Mixed 1	Mixed 2	Forest	Average
Width	2.83	1.79	4.41	4.24	3.3175
Depth	0.34	0.3	0.12	0.3	0.265
XsectArea	4.56	5.32	4.7	5.65	5.0575

It is worth noting that some error may be inherent within the data points themselves. Although the LiDAR data used in this study was certified by the State of North Carolina as meeting prescribed accuracy standards, it is worth noting that the “Built-Up” “Forest” and “Scrub” land classes (within which North Buffalo Creek would conceivably lie) for the Guilford County accuracy assessment contained only 18, 38 and 17 checkpoints respectively, fewer than the recommended minimum per class as established by the State’s accuracy guidelines. It is also unlikely that many of these checkpoints were taken from explicitly alluvial areas. Given what is known about LiDAR, it is likely that the distribution of error is uneven throughout the county, with error greater than 25cm in locations with a combination of heavy vegetation and sudden slope changes or steep slopes, such as areas immediately adjacent to stream channels.

Some model error may result from the loss of LiDAR returns in deep water sections of the channel, or in returns reflecting off the surface resulting in a false (smaller) channel depth and underrepresented overall channel capacity. Although water depth at surveyed reaches varied, in general it was observed that the portion of channel area below water represented a small fraction of the total channel capacity. Two reaches, the Landfill and NBC near Greensboro are the exception to this rule, where significant portions of the channel area lie below deep water. While we assume that deep water was not a major source of error throughout the model, its role in skewing channel capacity might increase downstream, as rural streams tend to exhibit lower banks with increased discharge, and consequently a greater proportion of the total cross-sectional area could lie below water.

6.2 - Influence of Changes Within the Fluvial System

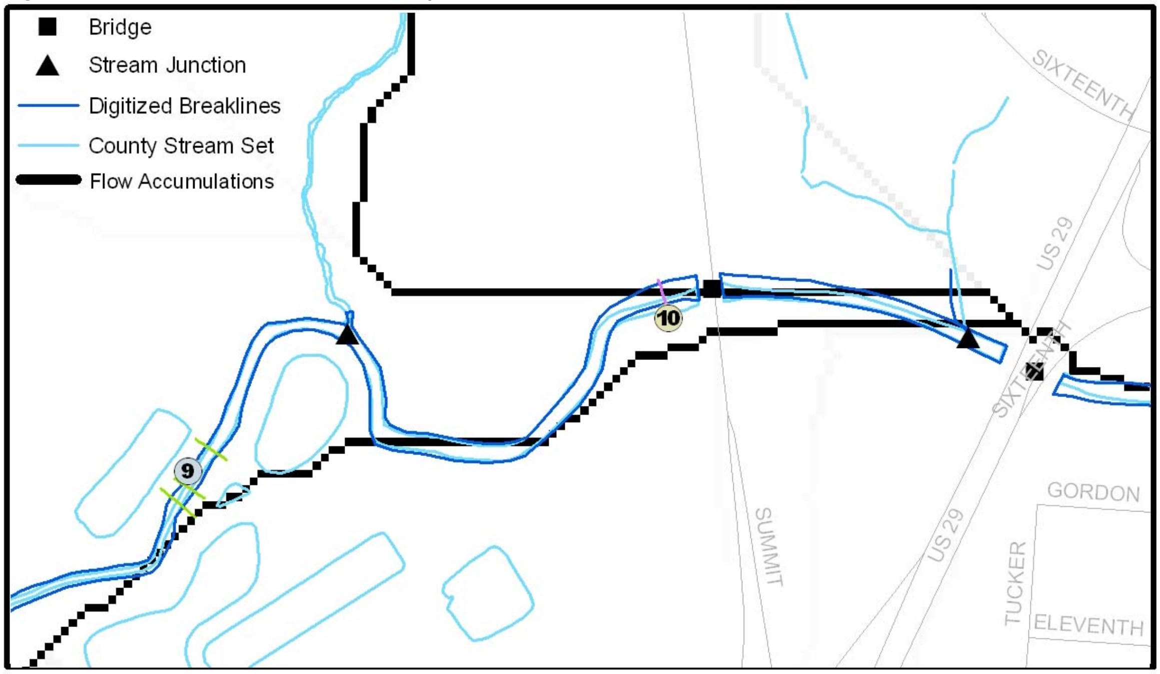
Temporal differences between data sources may result in discrepancies between observed measures. The LiDAR data was acquired in 2000-2001. Aerial photos, from which the breaklines were manually digitized, date to 2002. Field surveys were conducted between 2005 and 2008. While the fluvial system as a whole has been largely stable during this time period, there were noticeable local changes at many of the survey sites, including changes to point bars and lateral bars, channel widening due to slump/bank failure, and overbank deposition. It is possible that some of the differences between surveyed and modeled reaches can be attributed to significant local changes to channel shape and dimensions taking place between the time of the LiDAR flight and when surveys were conducted.

The role of active anthropogenic change on reach geometries must also be considered. The modeled features of several survey reaches, namely Westover 4 and 5 and Summit Upstream, deviate from what was observed in the

2002 aerial photographs and at the time of the surveys. Evidence on the ground of pipes and grading indicate that there may have been major construction in both areas at the time of the LiDAR acquisition, resulting in non-representative bank/floodplain elevation returns and modeled surfaces not representative of the current fluvial environment. At other reaches, evidence of local channel stabilization efforts such as rip rap and j-hook structures indicate that sections of the channel have been altered on an episodic basis.

Anthropogenic change may also introduce error with respect to the catchment drainage areas calculated from the 20m LiDAR set. In an urban area, it is likely that there are many modifications to the natural drainage patterns within a catchment. Thus local measures of change with regard to increasing drainage area taken from a model calculated from pour points may be inaccurate due to loss of first order streams, modification of stream junctions and drainage features that may not visible in aerial photographs such as storm drains. Figure 10 shows the Guilford County hydrology set location of a stream junction near Summit Upstream, and the corresponding junction as calculated by pour points. The junctions differ by 650 meters. As the tributary represents a 43% increase in total drainage area, knowing its actual location is of importance to understanding the accuracy of the modeled cross sections in this area and the role the increased discharge plays in downstream geometries.

Figure 10. Differences in Tributary Junction Locations



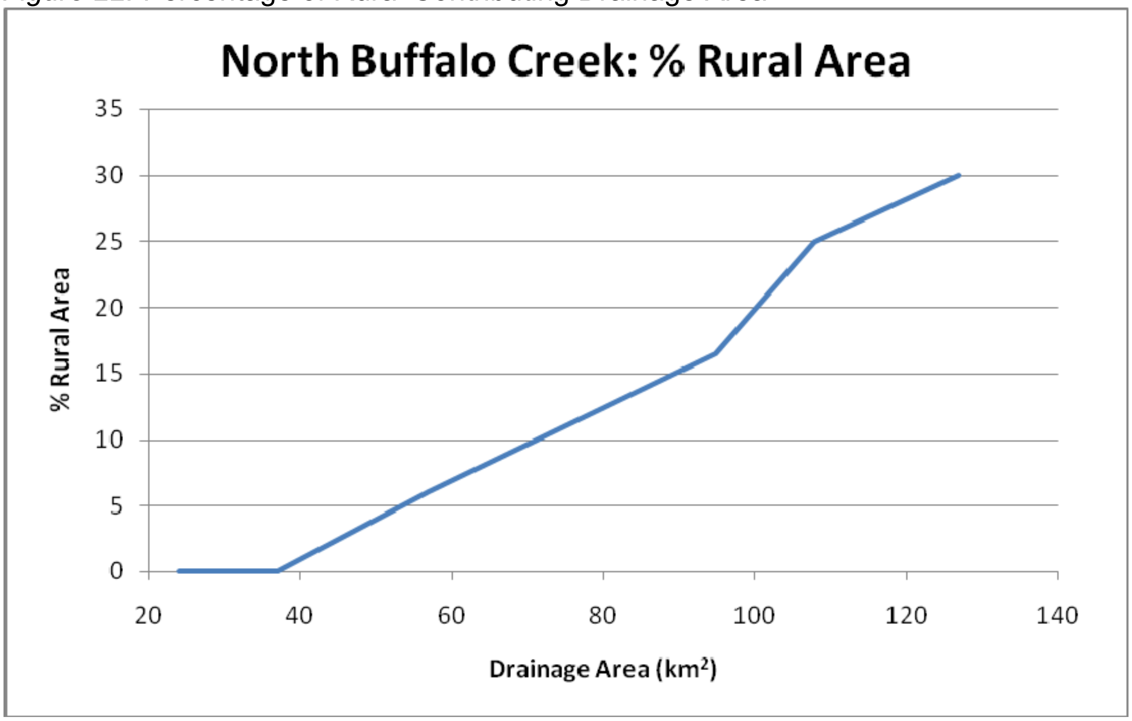
6.3 – Geomorphological Results

Although the reduction in enlargement ratio for cross sectional area is not smooth, the negative slope of the regression line in Figure 8 is solid and the extrapolation of downstream values yields a plausible result. In general, the transition appears to be linear, although the point distribution may also lead to a slightly asymptotic interpretation – meaning that enlargement ratios decrease more rapidly in the upstream samples than they do downstream. If this is the case, it would indicate that larger percentages of urbanized upland area have a greater effect on smaller headwaters streams, a finding that echoes the work of Hammer (1972). Further study, in the form of additional samples and verification on other Piedmont streams, would be needed to better evaluate this possibility.

It is possible that the decrease in enlargement ratio well within the urban boundary may be tied to the combined spatial and temporal nature of the city's historic development, as well as decreasing proportions of urbanized upland drainage area moving downstream. Over the last several decades major expansions of urban land uses have occurred mostly in the northwestern portions of the city, corresponding to the headwater areas of North Buffalo Creek. Thus the most enlarged areas reaches would be more likely to be found in areas experiencing recent development. The areas where enlargement begins to decrease are some of the oldest industrial areas in the city, many of which more than exceed Hammer's threshold of 30 years of active development (Hammer, 1972). These areas may have achieved some state of equilibrium. The channel has also potentially been the most affected by channelization and modification in these areas.

One might expect that enlargement ratios would decline in direct accordance with the percentage of watershed that is urban. That is, when moving downstream, the channel reaches the point at which 50% of the catchment is rural, that the enlargement ratios found within the city would have declined by 50%. For North Buffalo Creek, the percentage of rural area in the catchment hits 30% at the confluence of South Buffalo Creek. After this point, it increases at about 10% per 10 km^2 (Royall, 2008; Figure 11). South Buffalo Creek has similar catchment land use, so it is presumed that the rate does not decrease downstream from the confluence. If the rate of increase of rural land stays the same, the percentage of rural land will reach 50% well before where the regression line predicted rural cross sections, somewhere between 250-260 km^2.

Figure 11. Percentage of Rural Contributing Drainage Area



These trends have implications for environmental management. Geomorphic effects of Greensboro's urbanization extend into unincorporated eastern Guilford County toward the urbanizing area of Burlington in neighboring Alamance County. This means that as both cities continue to grow, the channel in the rural land use areas in between may experience instability and other symptoms of urban stream syndrome as those symptoms propagate downstream. Much of this land is agricultural, and there may be significant implications in the manner of changes to flood regimes, bank instability, and water quality. Attempts at mitigation of these effects could result in legal battles between landowners, the City of Greensboro, the City of Burlington, and Guilford County over costs and responsibilities.

6.4 – Discussion of Methods and Future Improvements

In traditional accuracy assessments, high correlation between randomly selected ground truth sites and corresponding model locations is generally associated with confidence in the model's ability to represent nature. In this study, ground truth locations were not chosen randomly, but by ease of access with regard to public property and right-of-way. This may introduce a siting bias based on the surveys, in that corresponding reaches were limited by geography rather than the quality of the LiDAR returns. The supplemental reaches sampled from the model may be more accurate than the modeled reaches corresponding to the surveys, in that they were selected from areas with high point densities, increasing the potential for points that accurately represent channel geometry. It is observed that the channel shape of individual survey sites differed greatly from a large number of the corresponding modeled sections. The largely trapezoidal bed shape was often modeled as a triangle where a suboptimal point spacing of only one or two in-channel points. When reaches were selected from the "best" areas, modeled shape was often trapezoidal and thus truer to the actual channel shape.

Extraction methods were heavily driven by prior knowledge of channel features, especially with regard to the selection of reaches by limited width and depth requirements, and may introduce bias into statistical results and analysis. As such, further study of additional Piedmont streams will be necessary to best evaluate the methods and observations of this study.

The supplemental inclusion of raw LiDAR data returns in the model, while improving overall point density in the channel, was limited by the lack of additional information, and any additional use (such as bank/floodplain definition) would have required extensive manual editing or an entirely different approach to modeling. Raw data inclusion in the filtering/modeling process would be significantly improved with additional metadata such as return information (first/last, intensity) and flight pattern, from which it may be possible to design an algorithm which specifically models the channel and its surrounding area utilizing criteria directed at capturing discrete areas and riparian features, as opposed to traditional filtering targeted toward large scale terrain modeling.

CHAPTER VII

CONCLUSION

This study demonstrates that channel terrain models derived for North Buffalo Creek from LiDAR do not represent specific cross sectional dimensions or shapes accurately, but do accurately represent the averaged dimensions of cross sections over channel reaches of 100-200m in length. Enlargement ratios for channel capacity area decrease downstream in a generally linear fashion with increasing drainage area. This decrease begins well within the Greensboro city limits. However, enlargement ratios do not decrease to rural proportions (enlargement ratio of 1) within the area of study. It is estimated that rural proportions may be reached at downstream locations with contributing drainage areas of between 400 and 450 km^2.

Although generally decreasing, individual reach enlargement ratios fluctuate in response to significant increases in contributing drainage area with major tributary junctions, generally in the downstream direction. In the case of the major junction with South Buffalo Creek, which doubles total contributing drainage area, enlargement might also extend upstream from the confluence.

Future study should include accuracy assessment of modeled cross-sections and further surveying of channel dimensions downstream in order to validate predictions. Similar techniques should be applied to other Piedmont streams in order to best evaluate results. With the application of ergodic logic, it may be possible to combine results from multiple areas to evaluate the interplay of drainage area, degree of urbanization, and other factors in the examination of the temporal nature of the geomorphic effects of urban stream syndrome.

Future exploration is also recommended with regard to the use of raw LiDAR data. The development of algorithms to specifically target bare earth points in riparian settings, as well as the exploration of other interpolation options (kriging, etc.) could be invaluable in the development of models that more accurately capture channel dimensions at a local scale.

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Appendix A

Modeled Survey Location Data

Site	Width (M)	Residuals	Depth (M)	residuals	Cross Sectional Area (XSA)	Residuals	Rectangle XSA	Trapezoid XSA
Wesley Long	14.11	2.72	1.61	-0.01	10.28	-0.49	22.72	21.11
Westover 1	16.3	0.07	1.6	0.19	13.1	5.46	26.08	24.48
Westover 2	18.36	-1.68	1.77	0.02	19.44	0.93	32.50	30.73
Westover 3	14.4	2.43	2.5	-0.71	27.1	-6.01	36.00	33.50
Westover 4	20.3	-4.39	1.7	0.12	24.2	-6.37	34.51	32.81
Westover 5	17.5	-0.36	1.3	0.46	23.5	-2.70	22.75	21.45
Lower Latham 1	18.85	-0.78	1.94	-0.25	24.66	-5.15	36.57	34.63
Lower Latham 2	14.3	4.05	2	-0.27	22.4	2.07	28.60	26.60
Elm St 1	15.28	3.72	1.58	0.06	12.88	4.11	24.14	22.56
Elm St 2	17.17	0.44	2.06	-0.41	21.79	-7.54	35.37	33.31
Elm St 3	16.61	0.84	1.57	0.05	18.73	-7.43	26.08	24.51
Church St. 1	11.2	4.40	2.7	-0.90	10.5	4.16	30.24	27.54
Church St. 2	13.87	2.34	2.14	-0.34	16.36	2.10	29.68	27.54
Church St. 3	12	3.87	2.2	-0.38	12.9	4.35	26.40	24.20
Church St. 4	10.58	5.02	1.32	0.43	8.19	4.13	13.97	12.65
Summit Up	24.64	-7.96	1.96	-0.20	27.26	-8.91	48.29	46.33
Summit Down	12.01	4.67	1.46	0.24	9.07	5.36	17.53	16.07
White St 1	26.77	-10.62	1.83	0.01	30.06	-9.40	48.99	47.16
White St 2	15.19	0.41	1.1	0.67	7.87	5.45	16.71	15.61
White St 3	12.8	3.57	1.19	0.62	8.44	11.35	15.23	14.04
Landfill	15.8	2.27	1.6	0.08	14.69	4.02	25.28	23.68
NBCnG 1	17.5	-0.11	1.3	0.45	23.5	-1.69	22.75	21.45
NBCnG 2	20.39	-2.47	1.86	-0.11	24.6	-0.63	37.93	36.07
Creekview Up	24.57	-7.05	1.6	0.20	19.58	6.91	39.31	37.71
Creekview Down	22.7	-5.43	27.7	-0.01	40.86	-4.09	39.06	

Appendix B

Averaged Reach Survey and Model Data

Stream Reach Name	Survey				Model					
	Drainage Area	Width (m)	Depth (m)	Cross Sectional Area	Width (m)	Depth (m)	Cross Sectional Area (XSA)	Rectangle XSA	Trapezoid XSA	Adjusted XSA
Wesley Long	12.60	12.50	1.18	14.80	14.11	1.61	10.28	22.72	21.11	15.48
Westover	24.60	11.70	2.46	28.61	17.37	1.77	21.47	30.37	28.59	31.03
Lower Latham	31.00	16.95	1.87	31.75	16.58	1.97	23.53	32.58	30.61	33.89
Elm St	35.70	16.33	1.28	20.90	16.35	1.74	17.80	28.53	26.79	25.93
Church	36.80	9.23	2.48	22.98	11.91	2.09	11.99	25.07	22.98	17.85
Summit	57.10	12.00	2.00	23.98	18.33	1.71	18.17	32.91	31.20	26.44
White St	58.40	11.65	2.21	25.83	18.25	1.37	15.46	26.98	25.60	22.67
Landfill	88.40	16.50	1.65	27.20	15.80	1.60	14.69	25.28	23.68	21.61
NBCnG	96.00	15.15	2.18	33.00	18.95	1.58	24.05	30.34	28.76	34.61
Creekview	107.20	14.30	2.52	36.00	23.64	1.70	23.64	40.09	38.39	34.04
Huff Farm 2	233.00	3.70	22.00	76.75	15.34	2.84	31.67	43.57	40.73	45.20

Appendix C

All Data for Final Downstream Analysis

Stream Reach	Reach Name	Drainage Area (sqkm)	# Xsect Samples	Avg Width (m)	Avg Depth (m)	Avg XSA (sqm)	Avg Enlargement Ratio	Adjusted XSA (sqm)	Adjusted Enlargement Ratio	xr	Moving Avg
1	Wesley Long	12.64	1.00	12.50	1.18	14.80	2.85	14.80	2.85	5.19	
2	Westover	24.65	5.00	11.70	2.46	28.61	3.53	28.61	3.53	8.11	2.95
3	3.1-3.3	28.4	3.00	12.42	2.49	14.91	1.67	21.92	2.46	8.92	3.75
4	4.1-4.4	29	4.00	19.97	2.85	33.38	3.69	47.58	5.26	9.04	3.69
5	Lower Latham	31	2.00	16.95	1.87	31.75	3.36	31.75	3.36	9.45	3.54
6	Elm St.	35.7	3.00	16.33	1.28	20.90	2.01	20.90	2.01	10.39	2.51
7	Church St.	36.9	5.00	9.23	2.48	22.98	2.16	22.98	2.16	10.62	2.35
8	7.1-7.3	38.4	3.00	18.07	2.20	21.61	1.98	31.23	2.86	10.91	2.54
9	7.4-7.6	40.44	3.00	16.61	2.11	20.17	1.79	29.23	2.59	11.29	2.38
10	Summit	57.1	4.00	12.00	2.00	23.98	1.69	23.98	1.69	14.22	2.22
11	9.1-9.3	57.4	3.00	18.28	2.27	23.77	1.67	34.22	2.40	14.27	1.96
12	White St	58.4	3.00	11.65	2.21	25.83	1.79	25.83	1.79	14.44	1.97
13	11.1-11.3	59.1	3.00	15.50	2.18	17.15	1.18	25.03	1.72	14.56	1.95
14	11.4-11.6	59.5	3.00	21.31	2.23	23.71	1.62	34.15	2.34	14.62	2.03
35	btwn 14 & 15	70.6	4.00	22.29	2.01	25.61	1.41	36.78	2.03	18.11	2.42
15	12.1-12.4	73.9	4.00	22.55	2.49	34.29	2.03	48.83	2.89	16.90	2.85
16	13.1-13.4	74.6	4.00	25.70	2.57	43.44	2.55	61.55	3.62	17.01	3.08
17	14.1-14.4	86.9	4.00	27.17	1.91	36.09	1.92	51.35	2.73	18.84	2.78
33	btwn 17 & landfill	88.3	3.00	25.80	1.76	29.50	1.40	42.19	2.01	21.03	2.05
18	Landfill	88.4	1.00	16.50	1.65	27.20	1.43	27.00	1.42	19.05	1.69
19	NBCnG	96	2.00	15.15	2.18	33.00	1.64	33.00	1.64	20.13	1.69
20	17.1-17.3	97.2	3.00	19.35	2.27	28.56	1.41	40.88	2.01	20.30	1.83
21	17.4-17.6	104.9	3.00	19.67	2.36	27.58	1.29	39.51	1.85	21.36	1.94
22	18.1-18.3	105.6	3.00	18.12	2.49	29.54	1.38	42.24	1.97	21.46	2.24
23	19.1-19.3	105.9	3.00	24.10	2.52	43.88	2.04	62.16	2.89	21.50	2.28
34	btwn 23 & 24	106.2	3.00	25.10	2.41	32.90	1.38	46.92	1.97	23.80	2.18
24	20.1-20.3	107	3.00	19.76	1.96	25.47	1.18	36.59	1.69	21.65	1.77
25	Creekview	107.2	2.00	14.30	2.52	36.00	1.66	36.00	1.66	21.68	1.84
26	21.1-21.3	111.1	3.00	24.54	2.06	33.71	1.52	48.04	2.16	22.20	2.06
27	22.1-22.3	112.9	3.00	23.09	2.55	36.96	1.65	52.55	2.34	22.44	2.50
28	23.1-23.3	113.5	3.00	25.51	2.73	47.62	2.11	67.36	2.99	22.52	2.48
29	29.1-29.3	230.5	3.00	23.75	3.41	59.34	1.49	83.64	2.09	39.95	2.26
30	29.4-29.6	231.8	3.00	23.52	2.87	47.82	1.19	67.64	1.69	40.10	1.96
31	31.1-31.3	232.9	3.00	23.98	3.43	59.61	1.48	84.02	2.09	40.23	2.14
32	Huffine Farm	238.4	1.00	22.00	3.70	76.75	1.88	107.84	2.64	40.86	